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THE JUPITER ICY MOONS ORBITER REFERENCE TRAJECTORY

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The proposed NASA Jupiter Icy Moons Orbiter (JIMO) mission would have used a single spacecraft to orbit Callisto, Ganymede, and Europa in succession. The enormous Delta-Velocity required for this mission (nearly 25 [km/s]) would necessitate the use of very high efficiency electric propulsion. The trajectory created for the proposed baseline JIMO mission may be the most complex trajectory ever designed. This paper describes the current reference trajectory in detail and describes the processes that were used to construct it.

INTRODUCTION

NASA's cancelled Jupiter Icy Moons Orbiter (JIMO), could have had great potential for scientific discovery at each of the three large icy moons of Jupiter. The large icy moons of Jupiter have the three ingredients essential for life: water, certain chemical compounds, and an energy source (tidal heating and radiation). The Galileo orbiter returned evidence for a liquid or slushy water layer present below the frozen crust of the icy moons. The Jupiter Icy Moons Orbiter science goals would include finding the extent of liquid oceans, locate regions that may be capable of supporting life, and identify future landing sites.

The baseline JIMO mission would involve sending a single spacecraft to orbit Callisto, Ganymede, and Europa in succession. The enormous ΔV required for this mission (on the order of 25 $\frac{km}{s}$) would necessitate the use of very high efficiency electric propulsion. The JIMO mission would demand major strides in the technology of spaceflight.

The trajectory created for the proposed baseline JIMO mission may be the most complex trajectory ever designed. This paper describes the current reference trajectory in detail and describes some of the processes that were used to construct it.

Trajectory Design Challenges

The trajectory required for a low-thrust Galilean moon orbiter mission is unavoidably complex and challenging to design. Strong multi-body effects combined with low-thrust control of capture and escape around the icy moons make the trajectory design and optimization difficult. Low-thrust control of capture and escape introduces risks and opportunities not present in chemical propulsion trajectories.

Optimizing low-thrust trajectories, and in particular, trajectories that include escape and capture is inherently difficult. The continuous operation associated with low-thrust significantly increases the optimization complexity. High fidelity modeling of escape and capture requires a multi-body force model and gravity harmonics. However, a multi-body force model and gravity harmonics compounds the optimization complexity. To fully optimize an escape or capture trajectory, the origin or

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destination of the trajectory must be taken into account. Typically this involves optimizing an interplanetary trajectory simultaneously with a moon and/or planet centered spiral trajectory. However, optimizing a trajectory involving both an interplanetary leg and a planet centered spiral, an then a moon centered spiral introduces several very different time and distance scales into mathematical formulation. Widely varying time and distance scales are known to create difficulty for numerical optimization.

If there were an unexpected loss of spacecraft control at critical points during low-thrust capture or escape from the Galilean moons, then there would be a risk of moon impact. The risk arises from strong multi-body effects near capture and escape and the associated chaotic orbits. Impact with one of the Galilean moons could occur in as little as several days after loss of control. The design of the trajectory must try to reduce this risk. Optimization formulations do not generally take the risk of impact resulting from a loss of control into account.

Besides making trajectory design more difficult, multi-body effects can present opportunities to improve performance[1,2,3]. Finding and evaluating these opportunities requires time and advanced design tools, but the performance improvements can be large. For example, distant retrograde type escape and capture[10] from a moon can provide a dramatic increase or, alternately, decrease in the spacecraft's orbital energy relative to the central planet compared to the moon's orbital energy with respect to the central planet.

The number of possible pathways between the Galilean moons presents another difficulty. As many as 6 or 7 moon flybys may be employed during each moon to moon transfer. The number of possible combinations of flybys and intermediate resonant orbits is very large. Most developments in the literature do not specifically address using low-thrust to transfer between Galilean moons. However several methods to analyze and sort pathways between the moons are useful in general. For example, the Tisserand graph method[4,5] provides a means to analyze alternate pathways.

APPROACH

This paper describes an optimal trajectory that begins in an injection state near the Earth and ends in low-Europa orbit. A spacecraft following this trajectory will orbit Jupiter, Callisto, and Ganymede in succession before orbiting Europa. The optimization objective is to maximize the final spacecraft mass in the low-Europa orbit subject to numerous constraints including a total flight time constraint, and given a fixed initial spacecraft mass in the near Earth injection state. An additional objective is to minimize the total integrated radiation dose of the spacecraft. This additional objective translates into a goal of minimizing the transfer time between Ganymede high orbit and Europa science orbit. The optimization variables include the free variables in the initial near-Earth injection state, the thrust vector as a function of time, flyby or multi-body interaction times, interaction geometries, arrival times, and departure times. The optimization algorithm called Static/Dynamic Control[7] (SDC) embodied in the program "Mystic" version 8.4.3 was used to design the final high-fidelity trajectory. SDC is a general, second order optimization method based on the Hamilton, Jacobi, Bellman equation and is distinct from both parameter optimization and the calculus of variations. Solutions obtained using SDC satisfy both the necessary and sufficient conditions of optimality. Trajectories are integrated with a multi-body force model, gravity harmonics, and finite burns.

Preliminary, low-fidelity investigations of the performance trade space for Earth departure times versus Jupiter arrival times was conducted using the patched conic low-thrust program called "MALTO"[11] and the two-body integrated program call VARITOP[12]. The program MALTO uses parameter optimization to solve a discretized approximation of the low-thrust. MALTO models low-thrust as series of impulsive maneuvers joined by conics. The program VARITOP uses the Primer Vector method to compute thrust directions and on and off times. Both VARITOP and MALTO execute quickly so large scale parametric studies can be completed in a reasonable time. Neither program can be used for high-fidelity design or design of trajectories in multi-body regimes.

The program VARITOP was used to generate thousands of optimal trajectories with various fixed flight times from Earth to Jupiter without intermediate gravity assists. The program MALTO was used to generate thousands of optimal trajectories form Earth to Jupiter using intermediate gravity assists from Venus, Earth, and Mars[13,14,15]. Although many promising gravity assist options were identified, it was decided that no intermediate gravity assist between Earth and Jupiter would be used in this reference trajectory. A gravity assist could be used in future reference trajectories to obtain more mass margin, if needed.

Once an approximate performance and flight time was identified for the Earth to Jupiter trajectory based on low-fidelity tools, the high-fidelity tool Mystic was used to design the complete reference trajectory. Mystic was first used to perform a limited, but high-fidelity trade study in flight time covering a range around the selected low-fidelity trajectory's flight time. In this way, the best transfer from Earth to Jupiter in the true multi-body model was obtained. The Mystic high-fidelity trade study was used as a guide for developing the final high-fidelity reference trajectory.

The dates and performance associated with the Earth to Jupiter leg changed significantly between the low-fidelity VARITOP (two-body) optimization and the high-fidelity Mystic optimization. This was expected. Optimizing capture and escape trajectories with a multi-body force model results in a significant improvement in the flight time and mass delivered compared to patched two-body formulations[2]. This is particularly true for massive body rendezvous. Strong points of the SDC approach embodied in the program Mystic is its ability to find and exploit multi-body phenomena and handle widely varying physical scales.

The trajectory was optimized in three major parts. The reason the trajectory was optimized in parts was because the trajectory is far too complex (requires more than 1,000,000 integration time steps) to optimize in a single piece. The trajectory was divided in such a way as to minimize the impact of piecewise optimization. For example, there is little useful control freedom in the low-altitude spiraling portions of the trajectory. Hundreds of powered revolutions are required with little change from one revolution to the next. Full optimization provides negligible improvements in performance compared to a simple control law of thrusting. Since low-altitude spiraling is not dependent on body phasing and does not require optimization, it can be "separated" from the interplanetary and intermoon trajectory. Similarly, moon to moon transfers can be optimized separately because the frequency of a repeated phasing between any two Galilean moons is on the order of only a few days. The trajectory was optimized piecewise as follows: I. Near Earth injection state to Callisto high-level orbit. II. Callisto mid-level orbit to Ganymede high-level orbit, and finally, III Ganymede mid-level orbit to Europa high-level orbit. Low-altitude spiraling around the Galilean moons was in many cases independently optimized and in a few cases integrated with a simple control law.

Spacecraft Parameters

Spacecraft wet mass and thruster performance parameters are provided in Table 1. The JIMO spacecraft was designed to carry both high specific impulse ion thrusters and lower specific impulse Hall effect thrusters. The spacecraft is assumed to be able to operate in two modes. One mode uses only ion thrusters, the other mode uses a combination of both ion and Hall thrusters. The use of only the ion thrusters provides the most efficient use of propellant at the expense of a much lower thrust level. The combination mode permits a relatively rapid change in velocity when absolutely needed to reduce impact risk and/or flight time in the highly radioactive neighborhood of Europa. The increase in propellant mass required for the combination mode is offset by the reduced radiation shielding mass when the flight time in the vicinity of Europa is reduced. The combination mode was intended for use near Europa but was allowed to be used at any point in the reference trajectory.

Table 1

SPACECRAFT PARAMETERS

Parameter	**value**
Spacecraft wet mass at near-Earth injection	36,000 kg
Power available to propulsion system	180 kW
Ion Thruster Specific Impulse	7000 seconds
Ion Thruster total efficiency	70.0 %
Hall/Ion Thruster Combination Specific Impulse	2280.9 seconds
Hall/Ion Thruster Combination total efficiency	44.097 %
Thruster duty cycle (modeled continuously)	98%

Spacecraft and Trajectory Constraints

Numerous constraints that impact the space of feasible trajectories were applied for various engineering and programmatic reasons. A list of the these constraints is provided in Table 2.

Table 2

TRAJECTORY AND SPACECRAFT CONSTRAINTS

Constraint	**value**
Near Earth injection date	During calendar year 2015
Near Earth injection energy	$C_3 \leq 10 \frac{km^2}{s^2}$
Capture at Jupiter (two-body energy=0)	On or before December 31, 2021
Thrust start-up after near Earth injection	$\geq$ 60 days
Allow lunar gravity assists	No
Allow planetary gravity assists	No
Forced coast during the first flyby of a Galilean moon on initial approach to the Jovian system	No thrusting from 14 days prior moon approach to 3 days after the subsequent Jupiter close approach
Forced coast during all subsequent Galilean moon flybys closer than 1000 km altitude	No thrusting from 1 day prior to immediately after the flyby
Minimum allowed flyby altitude for Galilean moons	200 km first flyby, 100 km subsequently
Orbital lifetime on approach and departure to the science orbits at Callisto and Ganymede (lifetime= time to impact given a loss of control at any point).	$\geq$ 14 days. The lifetime can be less than 14 days only for periods less than 12 hours in duration.
Science orbit parameters for Callisto, Ganymede, and Europa	Inclination = 70 to 110 degrees Altitude = 100 km Eccentricity $\leq$ 0.01 30 to 60 degree initial Sun phase $\geq$ 10 degree Δ Sun phase during the science orbit
Minimum stay times in each science orbit	Callisto: 120 days Ganymede: 120 days Europa: 60 days
Maximum thrust axis angular acceleration	$3 \ \frac{\mu Rad}{s^2}$

An investigation of alternate moon visit orders was completed with the conclusion that the best moon to visit first is Callisto, then Ganymede, and finally Europa. The deciding factor was not performance but rather total integrated radiation dosage. The radiation dosage is minimized with the Callisto, then Ganymede, and finally Europa order. The reference trajectory design was limited to this order. Another study was conducted to see which Galilean moon is the best to flyby for a gravity assist during the initial approach to Jupiter if the first target is Callisto. That study indicated that using Callisto for repeated flybys outperforms using Ganymede and Callisto in any combination for limited flight times. The reference trajectory design process used this result to eliminate the possibility of Ganymede flybys before the Callisto rendezvous.

The orbital lifetime constraint appearing in Table 2 presents a considerable design challenge. Any low-thrust spacecraft that is entering or departing orbit around a moon of Jupiter will by necessity spend a lot of time in high altitude, highly unstable orbits in the vicinity of the moon. Highly unstable orbits can lead to impact or escape in hours or days if the spacecraft losses control. This is in contrast to a hypothetical mission to the same moon using chemical propulsion. The high thrust of chemical propulsion can rapidly alter an impact safe hyperbolic state into an impact safe, stable, low-altitude captured state around a moon. In order to safely navigate the unstable orbital space around each moon using low-thrust, maps of the stable and unstable regions were constructed for each moon. Europa happens to have the most dangerous multi-body environment, so a great deal of effort was put into mapping and navigating Europa's stable regions[16,17,19,21]. It is well known that distant orbits around planetary satellites are far more stable in a retrograde motion then a prograde motion. For this reason, most of the design investigations centered on distant retrograde motion[6,10] of varying inclinations, however some attention was paid to prograde capture[17,21]. The reference trajectory was designed using retrograde motion around each moon. A stability map for Distant Retrograde Orbital (DRO) type motion for each of the three moons was developed[16] and relied upon heavily during the design process. Figures 1 - 3 illustrate one type of retrograde motion map produced for each moon, the so-called "Red Sea Plot". Blue areas on each map represent states that are stable for at least one hundred days. Red implies impact or escape in less than 10 days. The boundary between the blue areas and the yellow and red areas is sharp. The boundary between

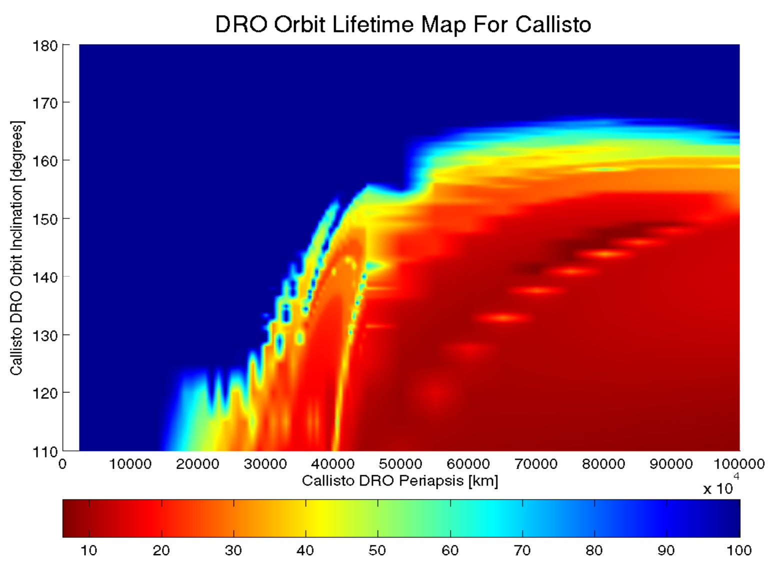

Figure 1: Retrograde motion stability map for Callisto.

the blue areas and the yellow and red areas remains in essentially the same place even when the stability test is extended to 1,000 year propagations. Each map is constructed based on the full ephemeris and multi-body propagation. Although the maps represent only a 2-dimensional slice of the many dimensional state space around each moon, this particular slice is very useful. The slice is useful because it demonstrates an everywhere stable continuous pathway from very high three-body type distant retrograde orbits all the way down to low two-body type captured orbits around each moon. Figures 1 - 3 illustrate that the size of the stable (blue) region decreases from Callisto to Ganymede to Europa.

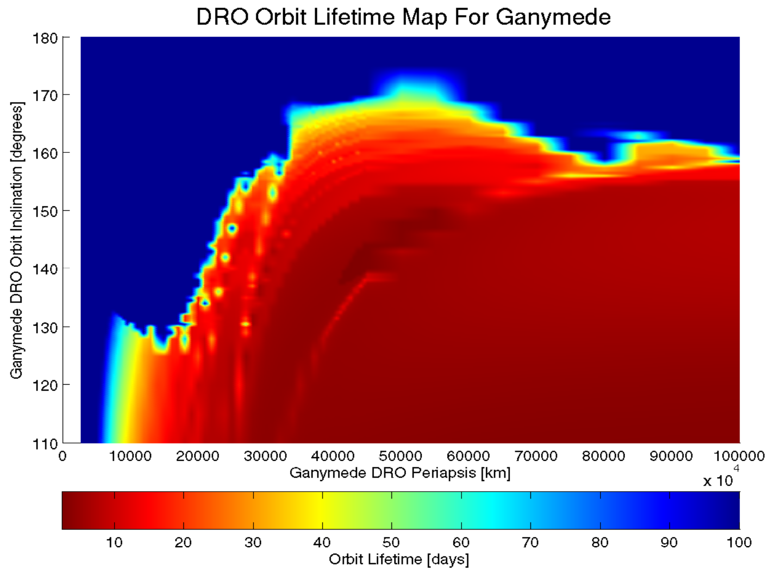

Figure 2: Retrograde motion stability map for Ganymede.

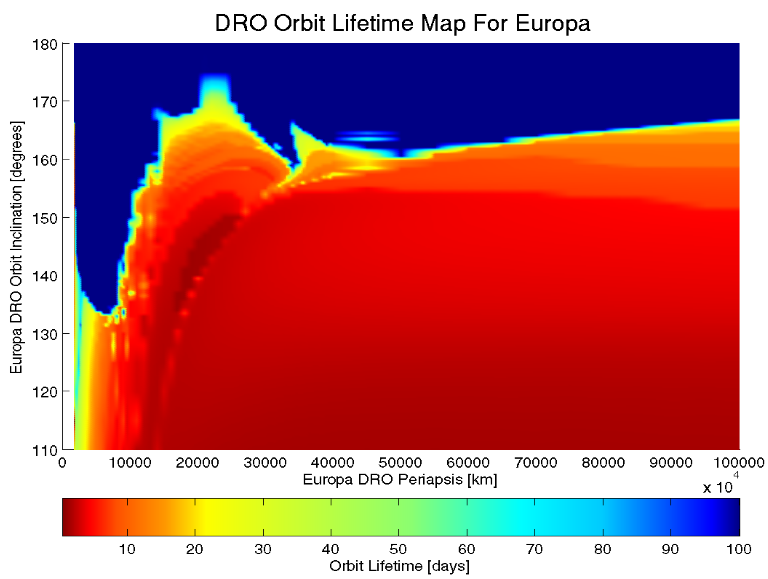

Figure 3: Retrograde motion stability map for Europa.

Recall that the required 100 km altitude science orbits at each moon are highly inclined (110 degrees). The stable regions limit the altitude that is used to perform plane changes. This limitation is most severe at Europa. A low altitude plane change requires far more ΔV than a high altitude plane change. At Europa this translates into an increase in propellant mass and even worse, an increase in flight time and radiation dose. For this reason, the lifetime constraint in Table 2 was only applied to Ganymede and Callisto. The goal of the Ganymede to Europa transfer is essentially a minimum flight time problem, allowing an increase in mission risk and propellant consumption to reduce radiation dose. The trajectory design process at Ganymede and Callisto attempted to stay on the blue regions in Figures 1 - 2 near the "coastlines" of their corresponding Red Sea Plots.

RESULTS

The analysis began with the selection of a low-fidelity optimal trajectory between Earth and Jupiter. The selected low-fidelity trajectory had a flight time of 2,200 days or 6.02 years. Arrival occurs at the latest allowed date in Table 2: December 31, 2021. This trajectory was selected based on a trade off or flight-time, performance, and launch date.

The high-fidelity tool Mystic was used to perform a trade study in flight time covering a range around the selected low-fidelity trajectory's flight time. The results of this trade study are illustrated in Figure 4. The higher, colored, curves represent the high-fidelity (massive Jupiter) optimal

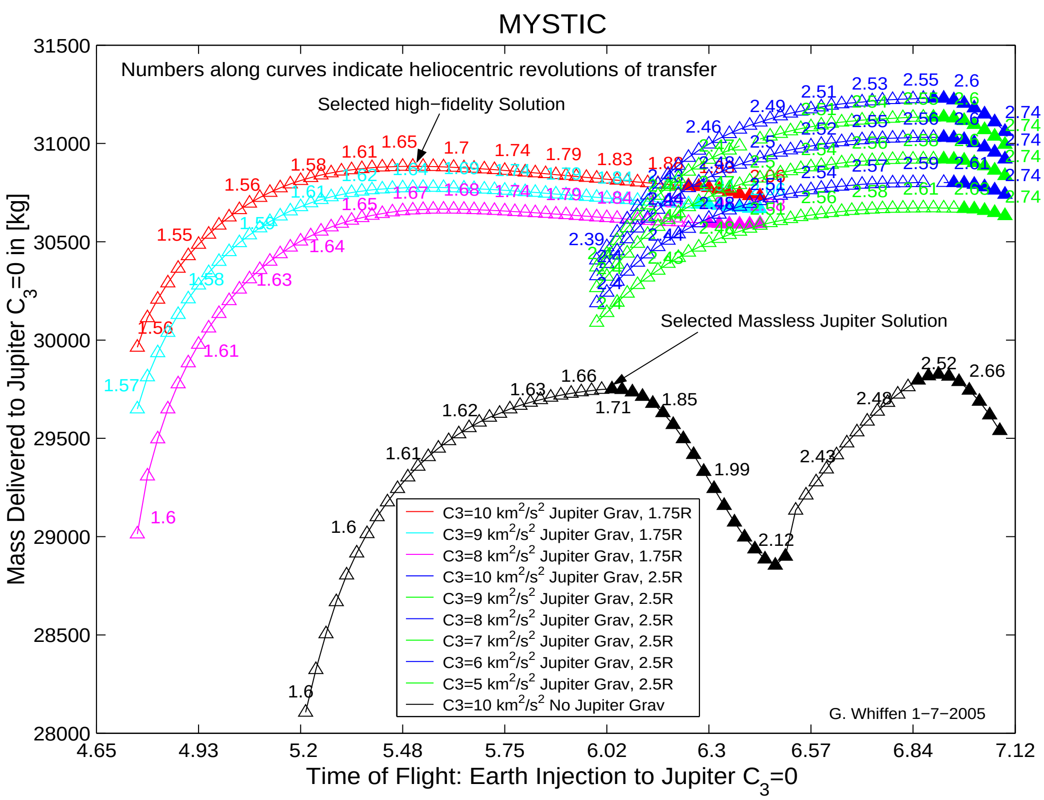

Figure 4: Earth injection to Jupiter capture flight time-performance trade study.

solutions from the near Earth injection state to Jupiter capture. The single lowest, black, curve is the low-fidelity (massless Jupiter rendezvous) optimal performance. Each triangle represents an optimized trajectory. Solid triangle markers correspond to cases where the optimal solution is constrained by the arrival date constraint of December 31, 2021. The selected 6.02 year flight time low-fidelity solution is indicated on the plot. The numbers along each curve indicate the number of heliocentric revolutions. There are two locally optimal families of solutions in both the low- and high-fidelity cases. One corresponds to transfers near 1.75 heliocentric revolutions, and another with near 2.5 heliocentric revolutions. There is a dramatic improvement in both mass delivered and flight time when a high-fidelity optimization that includes multi-body propagation is compared to the simple massless Jupiter rendezvous optimization.

The selected high-fidelity solution used as a guide for the design of the final reference trajectory was chosen to take advantage of the improvement in mass delivered without increasing the flight time. The top performing solution in the 1.75 revolution family was selected. The selected trajectory has a flight time of 5.5 years (2010 days) and is indicated in Figure 4. The selected high-fidelity solution in Figure 4 was only used as a guide for the final design of the reference trajectory. The final design of the reference trajectory involves using a gravity assist from Callisto near the first perijove passage on arrival at Jupiter. Both phasing and a performance gain from the Callisto flyby affected the final, optimal design.

Reference Trajectory Description

The trajectory begins in near Earth hyperbolic state that is consistent with an interplanetary injection from a 28.5 degree inclination parking orbit. The optimal injection energy is the maximum allowed by Table 2, $C_3 = 10\frac{km^2}{s^2}$. A low-thrust escape spiral from Earth was not selected because the flight time was deemed too long. The hyperbolic departure from Earth would require a very large new launch vehicle or several launches of existing vehicles with on orbit assembly. The optimal injection geometry is illustrated in Figure 5. A launch period analysis[18] concluded the mission is quite insensitive to launch vector error and many launch opportunities would exist for the mission described (this is typical of low-thrust missions in general). Launch is assumed to occur before

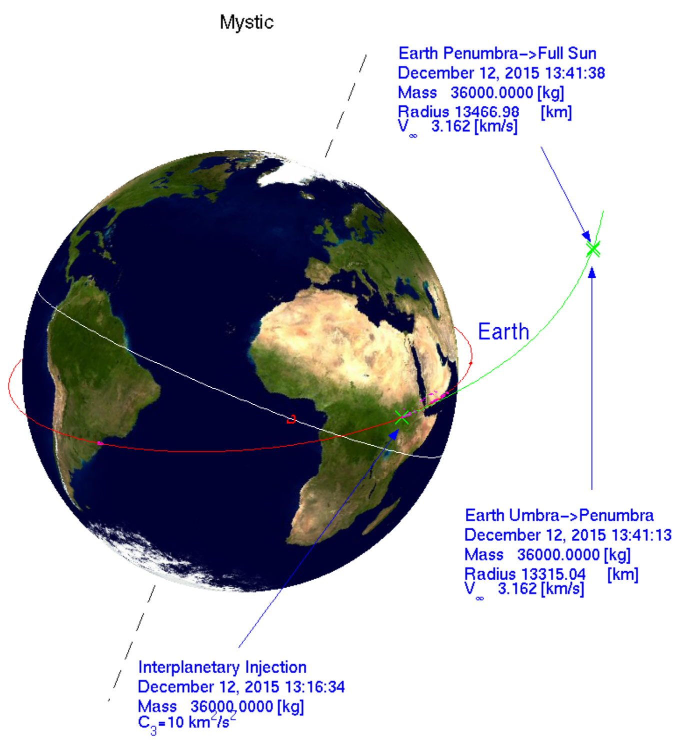

Figure 5: Reference Trajectory Earth injection.

December 12, 2015 so the interplanetary injection can be completed on this date. The Moon's gravity was modeled, but no close approach of the Moon occurs during departure. The free variables in the interplanetary injection state are the energy ($\leq 10\ \frac{km^2}{s^2}$), the argument of periapsis, and the longitude of the ascending node. The inclination was fixed at 28.5 degrees and the perigee radius was fixed at 6,778.14 km. The optimal departure asymptote declination is 5.59835 degrees and the right ascention is 173.7861 degrees in the Earth Mean Equator of J2000 reference frame.

Earth Injection to Callisto Orbit

The first end-to-end optimized portion of the reference trajectory begins in the near Earth injection state and ends in a high Callisto orbit. Figure 5 illustrates the Earth escape portion of the trajectory. A heliocentric view of the Earth to Callisto trajectory is provided in Figure 6. The small vectors along the trajectory indicate optimal thrust direction. The absence of vectors

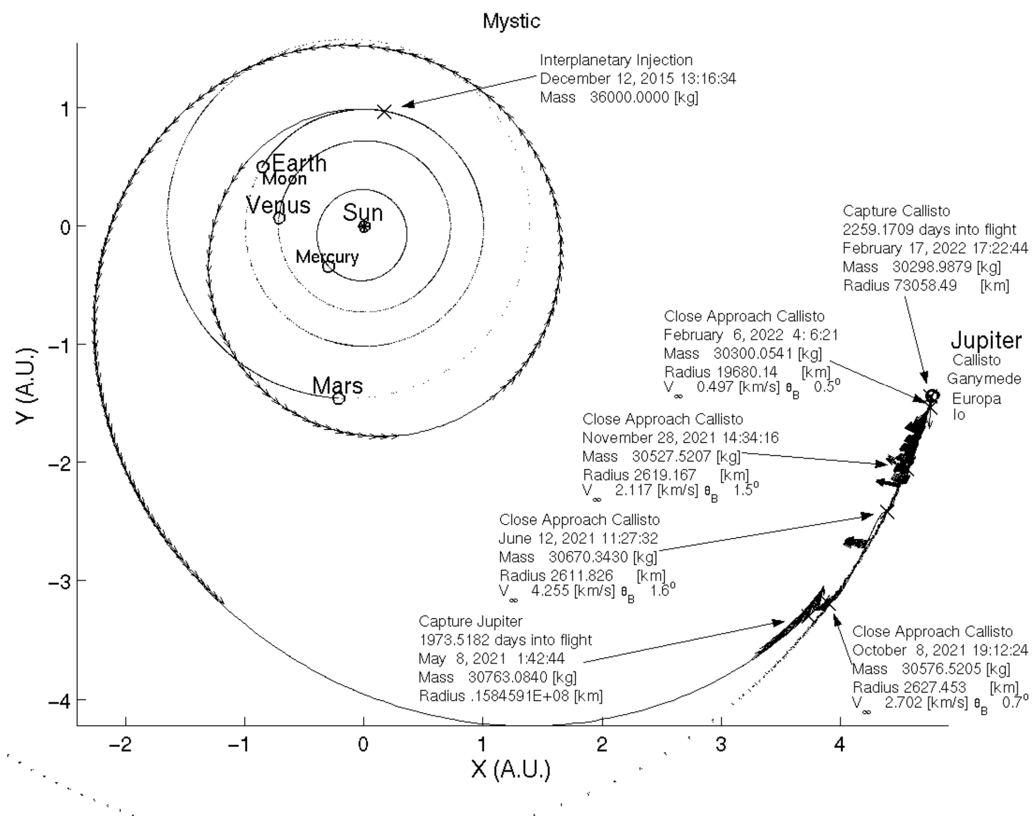

Figure 6: Reference Trajectory Earth to Callisto, heliocentric view.

indicate periods of coasting. There are three periods of coasting during the heliocentric phase. The first corresponds to the required forced coast during the first sixty days of flight for vehicle testing. The second two coasts are optimal coasts. The thrust vectors near Jupiter appear jumbled in the heliocentric frame because of the complex flyby sequence of Callisto and final capture into Callisto orbit. The reference trajectory requires four Callisto gravity assists before capture at Callisto 2248 days after the near Earth injection. Jupiter capture is achieved *before* any Callisto flyby occurs. Capture occurs on day 1973. Jupiter capture occurs somewhat sooner than the guideline optimal high-fidelity flight time of 2010 days (recall Figure 4). The added efficiency and phasing of Callisto gravity assists is responsible for the difference.

Figure 7 illustrates the Jupiter centered portion of the reference trajectory from Earth to Callisto orbit. A sequence of resonant flybys of Callisto was used to minimize propellant consumption to reach Callisto orbit after Jupiter capture. The sequence was 1:7 - 1:3 - 3:4 - DRO capture[10]. Many other resonant sequences are possible. For example, a 1:7 - 1:3 - 2:3 - DRO capture performs almost as well. The selection process for resonant transfers used in this trajectory segment is the same as what was used in the moon to moon transfers. The selection process is described in detail in the context of the moon to moon transfers. Figure 8 illustrates the Jupiter centered portion of

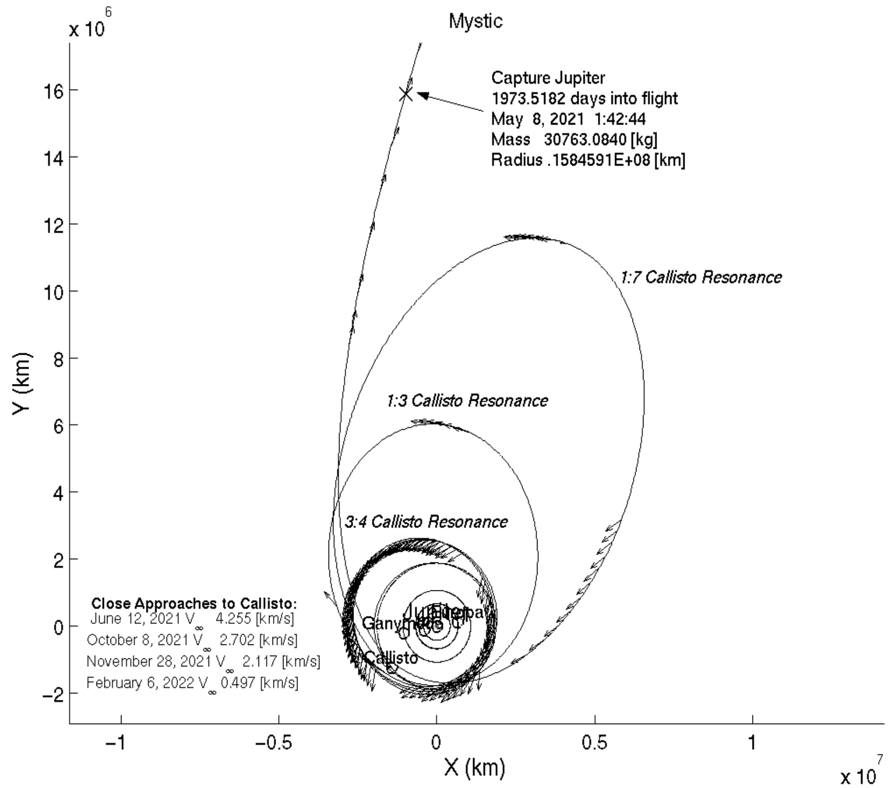

Figure 7: Reference Trajectory Earth to Callisto, Jupiter centered view.

the reference trajectory from Earth to Callisto orbit in the rotating Jupiter-Callisto frame. The type of capture at Callisto is nearly ballistic and is ideal for ending up in a retrograde orbit. The DRO type capture can also be thought of as a type of 1:1 resonance. The target science orbit at Callisto is retrograde and highly inclined at 110 degrees. The capture at Callisto results in an orbit of approximately 140 degree inclination. The rest of the plane change is made during the spiral down to the science orbit.

The trajectory lifetime constraint in Table 2 is satisfied for the Earth to Callisto transfer. Figure 9 illustrates the fate of the spacecraft in the first fifty days after a complete loss of control at different times during the transfer. For example, if loss of control were to occur at a flight time of 2120 days, then a close approach of Callisto without impact would occur in about 8 days and the spacecraft would not impact anything for at least fifty days. The close approach is the result of the targeting of Callisto flyby number 1. At no time will an impact occur in under 14 days as required. Only the final Callisto flyby targeting results in temporary impact targeting. There is no threat from Earth injection to 2080 days into the flight, so the plot in Figure 9 begins at a time of flight of 2080 days.

The reference trajectory was continued from the large Callisto DRO down to the science orbit using optimization for the first 125 days. The goal of the trajectory optimization was to reach the lowest altitude near circular orbit as possible with near continuous thrusting without violating the loss of control or "orbital lifetime" constraint in Table 2. Figure 11 illustrates the fully optimized portion of the Callisto spiral down in a Callisto centered non-rotating frame. This trajectory segment involves stabilizing and shrinking the three-body DRO type orbit into an essentially two-body circular orbit with an inclination of 109 degrees and an altitude of 7397 km.

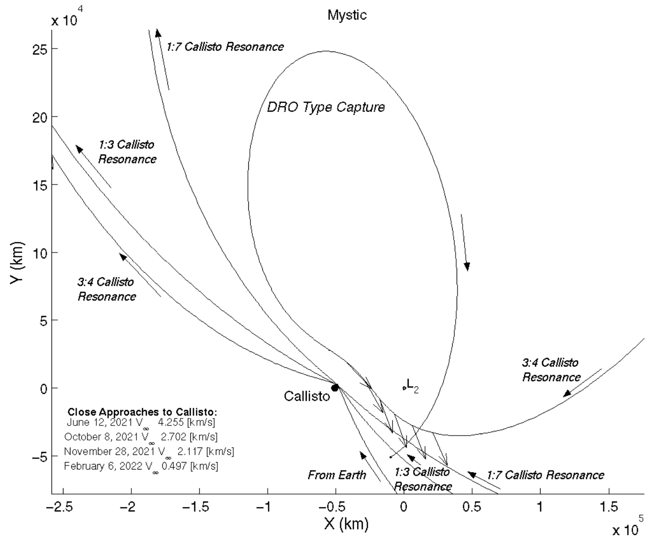

Figure 8: Reference Trajectory Earth to Callisto, Jupiter-Callisto rotating frame.

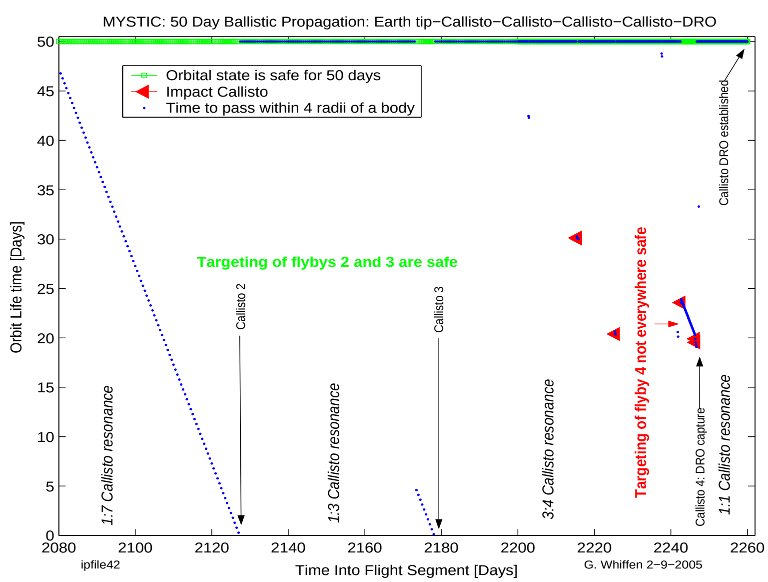

Figure 9: Reference Trajectory Earth to Callisto: loss of control fate.

Minimum propellant trajectory optimization will not generally obey the orbital lifetime constraint. In fact, optimization is most likely to disobey the orbital lifetime constraint. This is true because intermediate orbital states that are inherently unstable can often be used to achieve transfer objectives using little propellant. In the context of the so-called "Red Sea Plots" (Figure 1 - 3) this means that a fuel optimal transfer between two points in the blue (stable regions) that happen to be near the coastline (blue-red boundary) will involve an excursion into red states that are highly unstable. To counteract this tendency, the transfer to Callisto science orbit was computed as a sequence of optimal transfers between "waypoints". Each adjacent set of waypoints are selected such that the optimal transfer between them everywhere obeys the orbital lifetime constraint in Table

2. In practice, this requires multiple candidate waypoints to be tested until a satisfactory set of waypoints is determined. This process is illustrated in Figure 10. Figure 10 indicates the location of some of the candidate waypoints and the selected waypoints for the Callisto spiral down. The red,

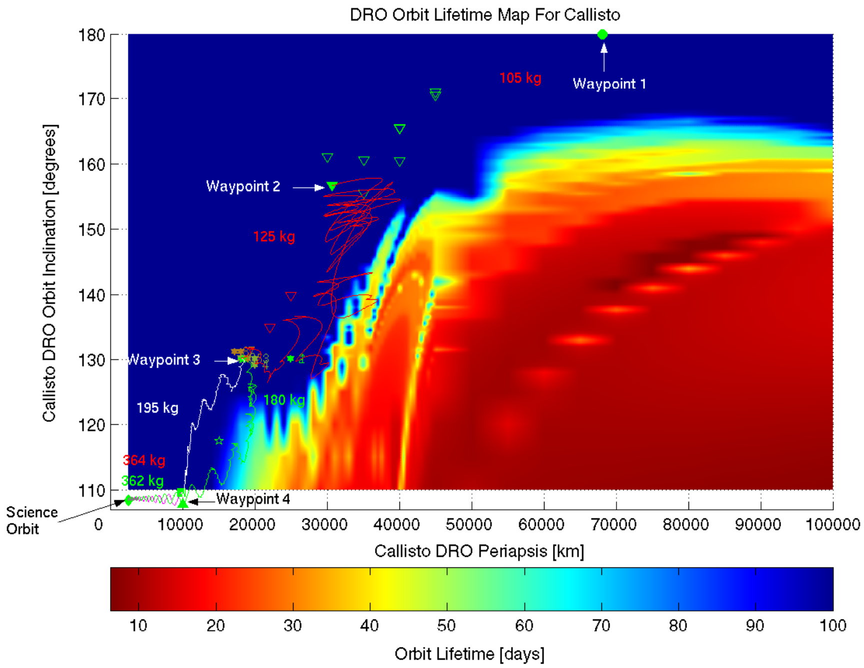

Figure 10: Reference Trajectory Callisto spiral down: waypoint design.

white, and green curves in Figure 10 show (approximately) where intermediate orbital states during transfers occur on the Red Sea Plot. If intermediate orbital states occur in the red regions, then it is likely that the orbital lifetime during these intermediate orbital states is very short. Successful waypoints are chosen close to the blue-red boundary for efficiency, but far enough from the boundary and close enough together that the optimal transfer between them does not stray into the dangerous red states. An example of two transfers that have very different characteristics is provided between the selected waypoint number 3 and candidate waypoints 4. One transfer is illustrated by the white curve between waypoint 3 and waypoint 4, the other transfer is illustrated by the green curve. The propellant usage is indicated next to each curve. The green transfer requires 180 kg of propellant to move between waypoint 3 to the vicinity of waypoint 4. The white curve is “safer” in that it stays in the deep blue but requires 195 kg of propellant. This tradeoff between relative risk and propellant consumption is common around all of the moons. The tradeoff becomes more severe for moons nearer Jupiter because the safe blue region becomes smaller.

A line between waypoint 4 and the science orbit is entirely inside the blue region of Figure 10 so the remaining transfer is inherently low-risk. The trajectory was completed to the Callisto science orbit (from 7397 km altitude, inclination 109.5 degrees to 100 km altitude, 108.4 degree inclination) using a simple continuous thrust control law. The control law determines the thrust direction according to the following algorithm. Let $\hat{u}$ represent a unit vector parallel to the spacecraft velocity relative to Callisto. Let $\hat{x}$, $\hat{y}$, and $\hat{z}$ denote unit vectors in an inertially fixed or some rotating frame. The thrust direction unit vector $\hat{T}$ is then given by

$$\hat{T} = \frac{\pm\hat{u} + a\hat{x} + b\hat{y} + c\hat{z}}{|| \pm \hat{u} + a\hat{x} + b\hat{y} + c\hat{z}||}, \tag{1}$$

where the a, b, and c are supplied constants. The sign of $\hat{u}$ is selected to be negative if spiraling down and positive if spiraling up. The effect of a, b, and c is to "skew" the spiral in one direction or another. In practice, the control law permits good control of the orbital eccentricity. The eccentricity will generally wander away from 0 when a, b, and c are all zero due to secular terms from gravity harmonics or multi-body effects. The constants a, b, and c are selected in a simple trial and error process until the final eccentricity is within acceptable limits. In this transfer, the frame used for $\hat{x}$, $\hat{y}$, and $\hat{z}$ was the ecliptic and equinox of 2000 and the values needed for a, b, and c are (0.0395,0,0). An empirical analysis demonstrated that as long as the required constants a, b, and c are small (typically < 0.1), then the control performance differs little from the fully optimal performance for the same transfer ($< 2\%$).

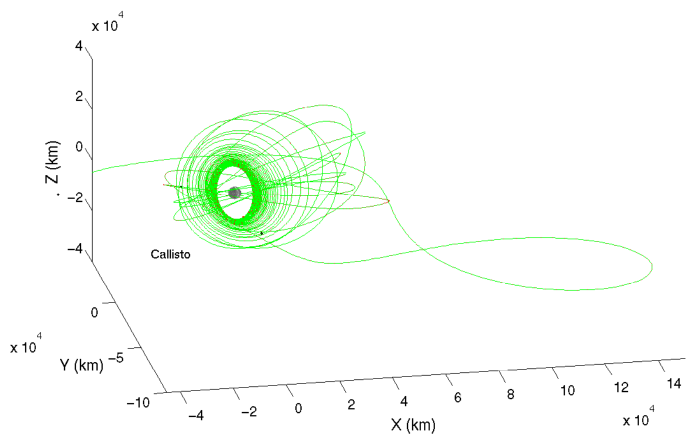

Figure 11: Reference Trajectory high altitude Callisto spiral down from waypoints 1 to 4.

The fate of the spacecraft given a 50 day loss of control is everywhere impact free during the spiral down to Callisto science orbit. The science orbit would require no orbital maintenance during the 120 days on station based on the available 3x3 harmonic field developed from Galileo flybys. This result may change when a more accurate gravity model for Callisto is developed. Improved gravity fields will need to developed during the later part of the spiral down phase[20].

The spiral up from Callisto science orbit was started using the control law (1) with a, b, and c set to zero since precise eccentricity control is not important during the spiral up. The transfer using the simple control law began with ϵ=0.006, inclination=108.9 degrees, a=2503.5 km and ended with ϵ=0.012, inclination=107.7 degrees, a=10004.23 km. From this point up to high altitude DRO a waypoint strategy was used. It usually turns out that successful waypoints on the Red Sea Plot for the spiral down can be re-used for the spiral up.

Callisto high orbit to Ganymede high orbit

The transfer from Callisto high orbit to Ganymede high orbit is the second of the three main end-to-end optimal transfers. The motion in Callisto high orbit before escape is similar to the three-body DRO. There are many possible sequences of intermediate flybys and moon resonances that can be used to from Callisto to Ganymede. The process for selecting a sequence for the reference trajectory is as follows. First, flight time is critical so all long period resonances like 10:17 Ganymede are immediately eliminated from selection. Second, each flyby to transfer from one resonance to the next is used to the greatest effect. The greatest effect is achieved when the flyby reduces the orbital energy with respect to Jupiter as much as possible and, at the same time, places the spacecraft into a new low-period resonance. To facilitate the design process, an energy level chart was produced for all selectable Callisto and Ganymede resonances. An example for Callisto is provided in Figure 12.

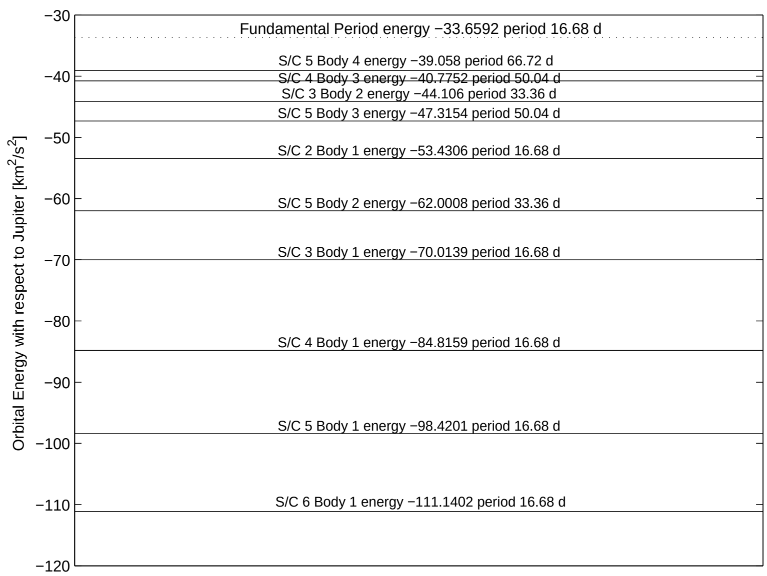

Figure 12: Callisto resonant orbital energies with periods less than or equal to 4 times the period of Callisto (66.7 days).

With the aid of charts like Figure 12, the design process is begun by first computing an optimal transfer to just escape Ganymede (depart the DRO) and obtain the lowest orbital energy with respect to Jupiter as possible. Note that a high altitude DRO around Callisto is adjacent to (in the three-body representation) both significantly larger and significantly smaller two-body-like orbits around Jupiter when compared to Callisto's orbit around Jupiter. This adjacency allows for very little thrust to leave Callisto's vicinity and entire a much smaller or much larger orbit around Jupiter than Callisto's orbit around Jupiter. Figure 13 illustrates four different locally optimal transfers to minimum energy orbits around Jupiter in a Jupiter-Callisto rotating frame. All four transfers depart from the same state. The lowest locally optimal Jupiter relative energy obtained was -40.36 $\frac{km^2}{s^2}$. This energy falls just short of the energy needed for the spacecraft 4 : Callisto 3 resonance at -40.7739 $\frac{km^2}{s^2}$. The best obtainable resonance is the spacecraft 5 : Callisto 4 resonance. The 5:4 Callisto resonance was selected for the reference trajectory. After 5 revolutions around Jupiter the spacecraft would re-encounter Callisto. The flyby is optimized to produce the lowest possible orbital energy with respect to Jupiter after the flyby. In this way it was found that perijove cane be lowered somewhat below Ganymede's orbit. Therefore it is possible to encounter Ganymede after only one half revolution around Jupiter after encountering Callisto (given proper phasing). This fact was used in the reference trajectory.

The Ganymede flyby was also optimized at first to minimize the resulting orbital energy of the spacecraft with respect to Jupiter after the flyby. With a orbital energy resonance plot similar to Figure 12 for Ganymede, the best obtainable, short period resonance was found to be 3 : 4 Ganymede resonance. The reference trajectory then makes use of the fact that a nearly ballistic capture to a large DRO around Ganymede is possible from the 3 : 4 Ganymede resonance.

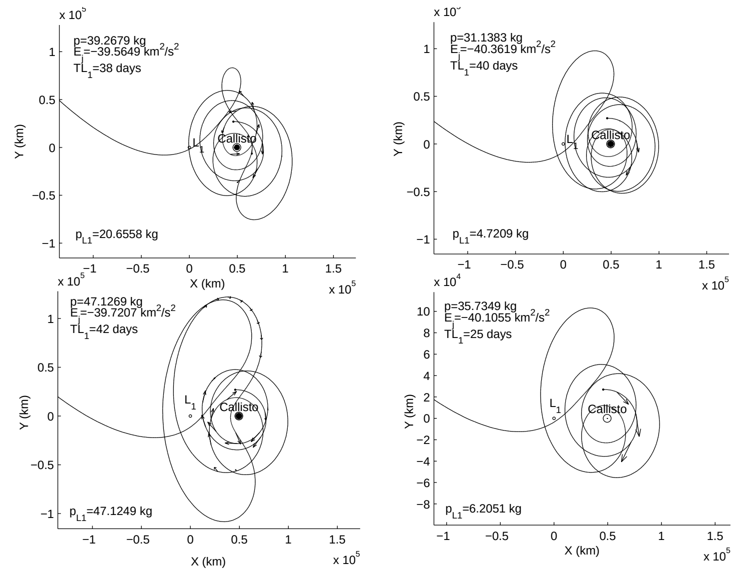

Figure 13: Four different locally optimal transfers to minimum energy orbits around Jupiter in a Jupiter-Callisto rotating frame.

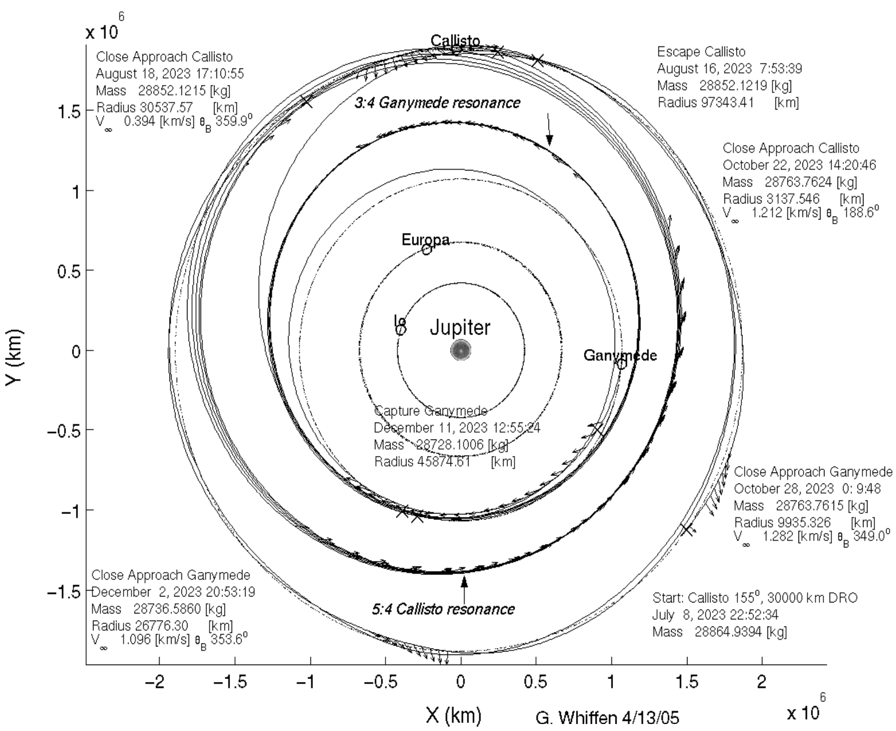

Figure 14: Reference Trajectory Earth to Callisto, Jupiter centered view.

Once the sequence of flybys and resonances were selected, the high fidelity tool Mystic was used to perform an end-to-end optimization of the complete trajectory from Callisto high orbit to Ganymede high orbit. The optimized transfer from Callisto to Ganymede is illustrated in Figure 14

The total required ΔV for the transfer from Callisto escape to Ganymede capture was only 296 $\frac{m}{s}$ with a flight time of 117 days. These compare favorably with transfers found in the past of 407 $\frac{m}{s}$ and 184 days for a previous reference trajectory, and with the trajectory described in reference [10] which required 435 $\frac{m}{s}$ and 95 days. For further comparison, simple (no-gravity assist) spiral transfer would require 2,670 $\frac{m}{s}$ and 243 days. The trajectory described in reference [10] has a superior flight time because the 4 : 3 Callisto resonance could be used in place of the 5:4 Callisto resonance used in the reference trajectory. The lower energy resonance was obtainable in reference [10] because the assumed spacecraft has a significantly greater assumed thrust acceleration, however a significant increase in ΔV is required to reach the resonance immediately after departing Callisto's vicinity.

The appearance of the reference trajectory in the vicinity of Ganymede is provided in Figure 15. The orbital lifetime for the Callisto to Ganymede transfer met requirements and is illustrated

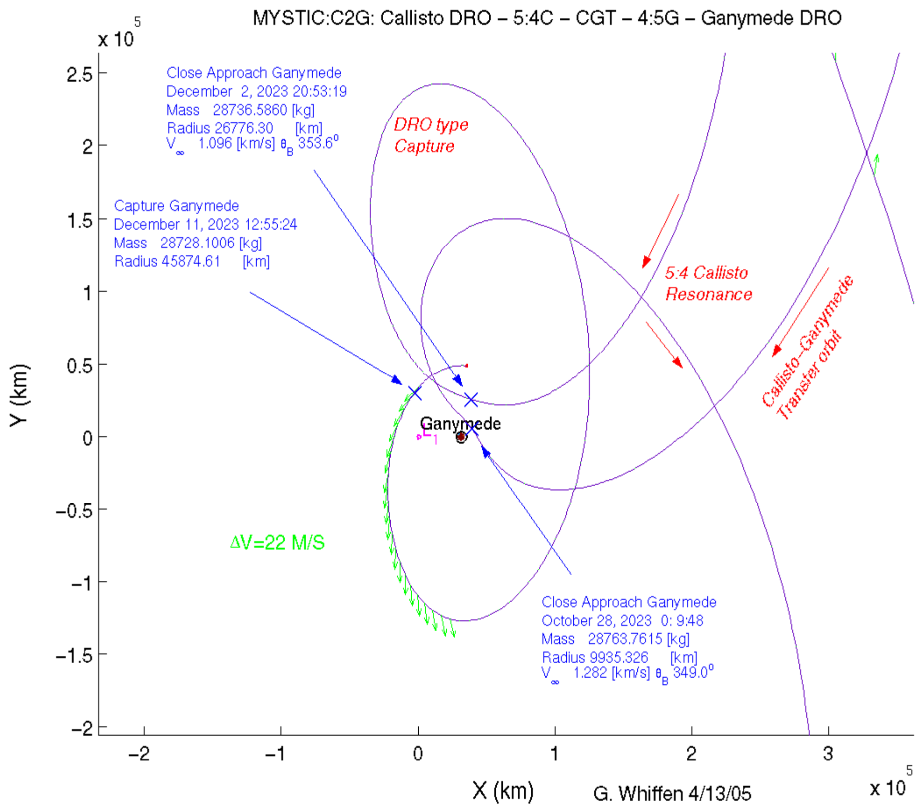

Figure 15: Reference Trajectory Ganymede capture, Jupiter-Ganymede rotating frame.

in Figure 16. A spacecraft loss of control could cause impact in under fifty days if the loss of control occurred in one of four time segments each less than 6 hours long.

Ganymede Spiral

The Ganymede spiral down and up trajectory was constructed in an analogous fashion to the Callisto spiral down and up trajectory described previously. The Ganymede spiral down is more challenging than the Callisto spiral down because there is less stable space in which to operate (compare Figures 1 and 2). A large plane change is necessary at low altitude to reach the high inclination science orbit at Ganymede while staying in the stable (blue) regions of Figure 2. Simple control laws for low altitude plane changes result in thrust vector angular accelerations that exceed

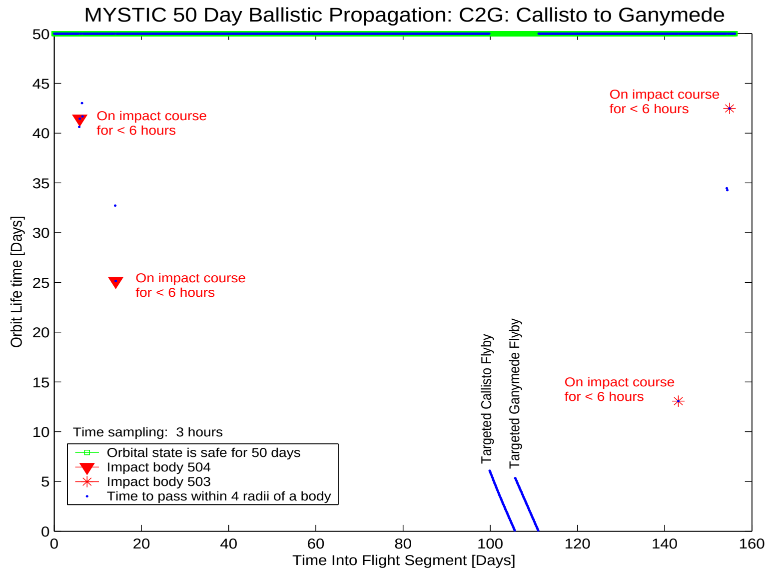

Figure 16: Reference Trajectory Earth to Callisto: loss of control fate.

the maximum limit in Table 2 of 3 $\frac{\mu Rad}{s^2}$. It was observed that fully optimal transfers generally have significantly lower thrust vector angular accelerations than simple control laws. For this reason, the spiral down at Ganymede was optimized all the way down to an altitude of 1770 km and an inclination of 110.1 degrees. The simple control law (1) with was used from 1770 km altitude to the science orbit at 100 km altitude. The frame used for the control law (1) was the ecliptic and

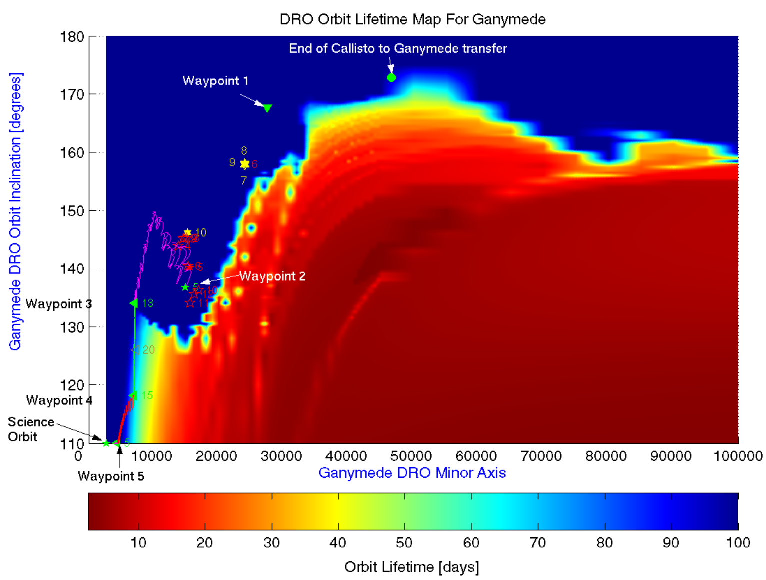

Figure 17: Reference Trajectory Ganymede spiral down waypoints.

equinox of 2000 and the values needed for a, b, and c are (-0.05,0,-0.01).

The optimal transfer between waypoints 3 and 4 is plotted in a non-rotating frame centered on Ganymede in Figure 18. The significant rotation of the node is a result of Jupiter's gravitational perturbation. The Ganymede spiral up used the same waypoints used on the way down in reverse

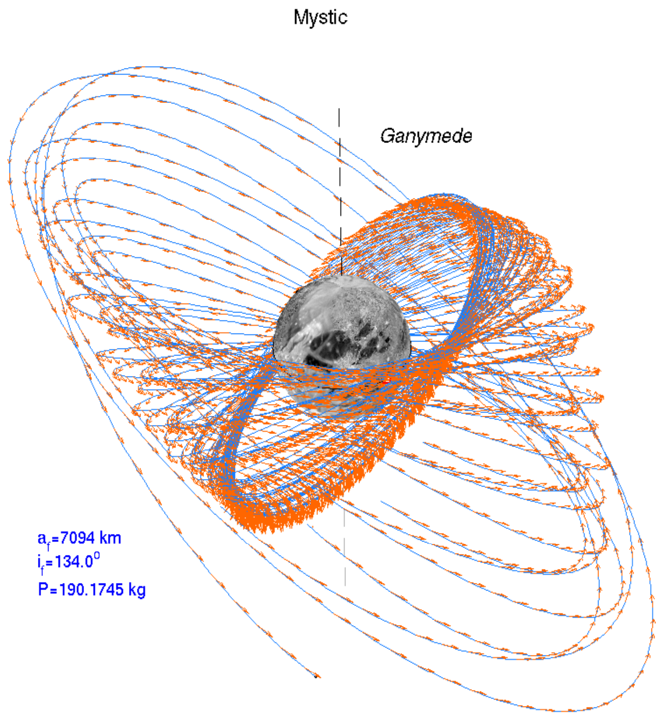

Figure 18: Reference Trajectory Ganymede spiral down from waypoint 3 to waypoint 4.

order.

Ganymede Mid-level orbit to Europa high orbit.

The transfer from Ganymede mid-level orbit to Europa high orbit is the third of the three main end-to-end optimal transfers. The goal of this transfer is different than that of the Callisto to Ganymede transfer. The most rapid practical transfer is desired because of the high radiation environment between Ganymede and Europa. The minimum flight time objective is at cross-purposes with the objective of minimum propellant and minimum risk. The orbital lifetime constraint in Table 2 is not applied to the Ganymede to Europa transfer. The spacecraft is assumed to carry Hall thrusters (see Table 1), but the Hall/ion combination thruster mode has not been used in the reference trajectory yet because of the minimum propellant objective. When and for how long to use the Hall thrusters presents another dimension to the design problem. Many different strategies were tested and compared. It was found that using the Hall/ion combination from the start of the Ganymede spiral out was not acceptable because the propellant usage was over 2,000 kg just to get from Ganymede's science orbit to a capture state around Europa. The best strategy discovered was to limit the use of the Hall thrusters to the vicinity of Europa. On the other extreme, transfers to Europa science orbit were attempted without using the Hall thrusters at any point. This option appears to be very problematic due to the weak control authority in high inclination high altitude orbits near Europa. High inclination high altitude orbits near Europa could not be reliably controlled with the low-thrust of the ion only propulsion mode. For the sake of short flight times, the approach to Europa involves high inclination high altitude orbits that are well inside the red (unstable) regions of the phase space plot in Figure 3. It was concluded that Hall thrusters are required for DRO type captures during the initial capture at Europa in the high inclination high altitude orbits. One halo type capture trajectory was successfully designed without the use of the Hall thrusters.

Once captured at Europa, Hall thrusters can be used to greatly reduce the time of flight during the spiral down. A trade study was conducted between radiation dose near Europa and propellant usage. It was concluded that the Hall thrusters should be used nearly continuously in Europa orbit.

The trade study of the Ganymede to Europa transfer involved both alternate Hall thruster use strategies and alternate Europa capture types. The capture type used at both Callisto and Ganymede was the so called DRO type capture which results in a stable retrograde motion around each moon. Alternates to this capture type were investigated[17,21] at Europa to reduce flight time given that the orbital life time constraint at both Callisto and Ganymede was not applied at Europa. Table 3 summarizes a few of the trajectories considered for the reference trajectory Ganymede to Europa transfer. All transfers begin in Ganymede science orbit with a spacecraft mass of 27,724 kg.

Table 3: GANYMEDE SCIENCE ORBIT TO EUROPA SCIENCE ORBIT (ESO)

ID	Capture Type	Resonances	Mass at ESO (kg)	Flight Time (days)	Ion Prop. (kg)	Hall/Ion Prop. (kg)
1	Halo	4:3G,3:4E,14:15E	26,543.87	296.16	1,180.32	0.00
2	DRO	4:3G,3:4E	26,180.66	316.71	1,149.16	394.37
3	Halo	4:3G,3:4E,14:15E	26,085.47	270.35	939.45	699.27
4	Halo	5:4G,3:4E,5:6E,7:8E	25,994.59	299.92	810.26	919.34
5	DRO	4:3G,3:4E	25,780.44	295.48	952.42	991.33
6	DRO	4:3G,3:4E	25,653.42	271.29	105.73	1,965.04
7	DRO	4:3G,5:7E,9:10E	25,636.68	382.65	882.28	1,205.23
8	DRO	4:3G,3:4E	25,394.60	272.84	759.23	1,570.35
9	DRO	4:3G,3:4E	25,093.31	261.99	690.14	1,940.74

The fastest transfer from Ganymede escape to Europa capture was discovered using the same procedure as was used for the Callisto to Ganymede transfer. The shortest flight time transfer first escapes from a large DRO around Ganymede to a 4:3 Ganymede resonance. Ganymede is then re-encountered 21.5 days after escape. The Ganymede flyby places the spacecraft on a trajectory to encounter Europa 2.6 days later after one half a revolution around Jupiter. The Europa flyby places the spacecraft on a 3:4 Europa resonance. After 14.2 days Europa is re-encountered and and the space craft can capture into an inclined DRO. The entire transfer requires only 38 days. A halo type capture requires a lower Europa approach velocity then is provided by the 3:4 Europa resonance. For this reason, the halo type captures in Table 3 require one or two more resonant steps to reduce the Europa approach velocity before capture. Halo type captures require more flight time between the escape at Ganymede and the capture at Europa compared to DRO type captures. However, Halo captures require less time to spiral down to the Europa science orbit than do DRO captures. The transfer with ID 9 was selected for the reference trajectory. This trajectory was selected primarily for its short flight time from Ganymede science orbit to Europa science orbit of 261.99 days.

Figure 19 illustrates the transfer from Ganymede to Europa. Figure 20 illustrates the first 41 days of the spiral down at Europa in a non-rotating frame. The outer orbits around Europa appear highly chaotic in the non-rotating frame of Figure 20. The orbits become regular inside of the Jupiter-Europa Lagrange point. A reversed (outer orbits are regular and inner orbits appear chaotic) appearance occurs for the same trajectory in a Jupiter-Europa rotating frame.

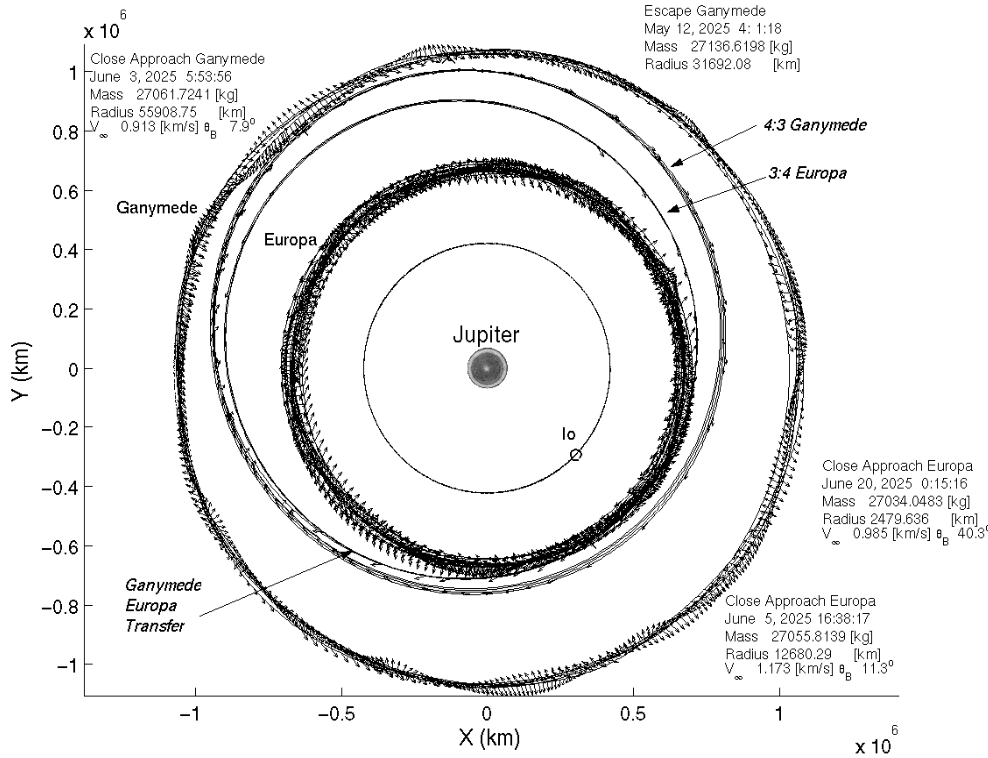

Figure 19: Reference Trajectory Ganymede mid-level orbit to Europa mid-level orbit.

Table 4: Summary of the JIMO Reference Trajectory

Leg Description	**Flight Time** [days]	**Propellant Usage** [kg]	ΔV $[\frac{km}{s}]$
Earth injection to Jupiter capture	1973.5	5237	10.792
Jupiter capture to Callisto capture	274.5	464	1.043
Callisto centered spiral down	217.4	793	1.821
Callisto science orbit	120.0	0	0.000
Callisto to Ganymede science orbit	633.8	1782	4.275
Ganymede science orbit	120.0	0	0.000
Ganymede to Europa science orbit	262.0	2631	3.396
TOTAL	**3601.2**	**10,907**	**21.327**

Conclusions

A low-thrust Galilean moon orbiter mission design requires end-to-end optimization of trajectories involving a near Earth injection state, an interplanetary leg, Jupiter centered spiral, and a Callisto centered spiral. The trajectory from Earth to Callisto has a dynamic scale change factor of 10,000 (the extremes are the heliocentric phase and the Callisto orbit phase). Widely varying time and distance scales are known to create great difficulty for numerical optimization. The SDC algorithm embodied in the program Mystic has been shown to be capable of optimizing high fidelity trajectories with as much dynamic variation as occurs in the Galilean moon orbiter mission. Even though the SDC algorithm is capable of optimizing a Galilean moon orbiter trajectory, the dura-

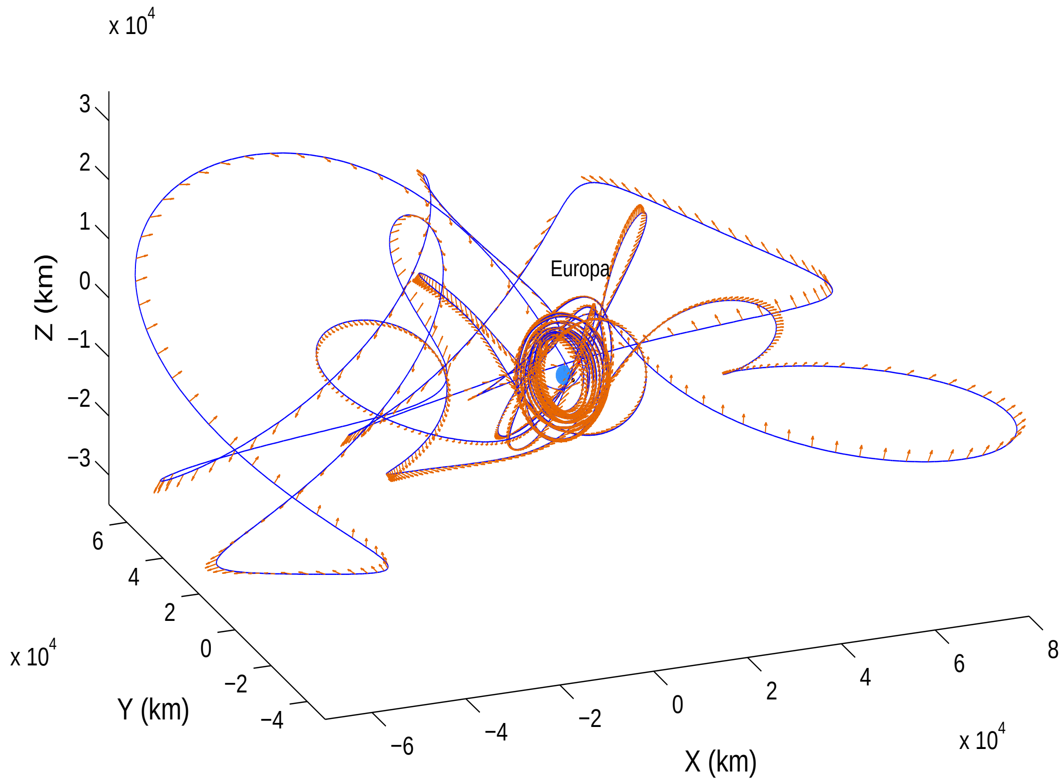

Figure 20: Reference Trajectory: The first 41 days of the Europa spiral down.

tion and complexity of the mission will make detailed trade studies difficult. Individual complete trajectories require a fair amount of time to construct, and optimize.

The impact risk resulting from unexpected loss of spacecraft control at critical points during low-thrust capture or escape requires significant analysis. Optimizing trajectories for mass performance more often than not results in trajectories with a high risk of Galilean moon impact resulting from unexpected loss of spacecraft control. A waypoint process was used to reduce this risk in the reference trajectory.

A method to generate very efficient, short flight time, sequences of resonant orbits was used to complete the transfers between Jupiter capture and Callisto; between Callisto and Ganymede; and between Ganymede and Europa.

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